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NASA TECHNICAL MEMORANDUM

NASA TM-76953

TWO-DIMENSIONAL WIND TUNNEL

(NASA-TM-76963) TWO-DIMENSIONAL WIND TUNNEL
(National Aeronautics and Space
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Seven year production of a two-dimensional wind tunnel facility with a total budgeted cost of 1,564,000,000 yen was completed at /1* the end of 1979. Operation tests were safely completed in July of this year and full-scale tests on wing section systems will finally begin in 1980. We will take this opportunity to comment on the background of this wind tunnel facility and its construction and to introduce the wind tunnel structure, operation test results, and future plans.

1. Background of the Two-Dimensional Wind Tunnel Facility

It goes without saying that a huge jumbo jet exceeding 300 tons is supported in air by its main wings. However, how such a delicate and fragile component can produce so much strength, and, once this is explained, how even better wings can be produced are important aerodynamic problems. Nevertheless, modern transport planes travel very quickly and the SST, which flies at a speed twice that of sound, has been developed. There can be no comparison of wings for flying near the speed of sound or at speeds higher than this and those wings that are used at relatively low speeds, which were mainly developed during World War II.

The most characteristic phenomenon that occurs with high speed wings is the production of shock waves. When a region of flow that exceeds sonic speed exists in the flow above the wing surface, pressure waves that appear from various locations on the wing surface gradually accumulate until the strongest and sharpest wave is formed. When this wave is formed, an increase in wing drag corresponding to the operational energy spent in producing this wave occurs. In addition, the flow easily reflects off the wing surface at the position corresponding to the source of this shock wave and at its downflow. When this flow reflection occurs, there is a reduction in the lifting

*Numbers in margin indicate foreign pagination.

power (power which lifts the plane) produced by the wings and an increase in drag. When this condition builds up, so-called shock wave stall occurs and normal flight conditions of the airplane cannot be maintained.

Heretofore, studies aimed at eliminating the effects of shock waves, which destroy the properties of wings during high speed flight, have been carried out. A breakthrough was made by 2 Piashii of the United Kingdom in the mid 1960's. He proved that there is actually a cross section of the wing where shock waves are not produced, even in high speed flow near sonic speed, which had been theoretically pursued by some researchers. He also explained the properties of the flow at this time. Many researchers continued with his studies and developed theories for shock wavefree wings. Our research lab also presented good experimental and theoretical results. Today the first stage in these studies has been completed and research is now being carried out not only on "shock wavefree transonic wings, but also on transonic wings that present a small increase in drag and have a high lifting power, even when shock waves are produced. These types of wings are all characterized by the fact that the surrounding flow is in a supercritical state (condition where a region having a speed exceeding sonic speed appears) and therefore, they are called "supercritical wings" to distinguish them from conventional wings. In short, the cross section of these super-critical wings is designed so that the damaging effects of the flow are not exerted on the back half of the wings because shock waves produced below the supersonic speed region are sufficiently weakened while lifting power is produced by employing a strong low pressure produced inside the supersonic speed region above the wings. As a result, the aerodynamic efficiency MxL/D of the wings rapidly increases in comparison to conventional wings because a high lift/drag ratio L/D of the wings can be maintained even though the maximum flight speed of the plane is even

higher. Since this aerodynamic efficiency is directly proportional to the transport efficiency ($\frac{\text{cargo weight} \times \text{distance}}{\text{amount of fuel consumed}}$), an increase in this value is an energy saving measure and plays a large role in economically improving aircraft transport. Consequently, research on this type of wing is being earnestly pursued by many countries throughout the world.

In Japan "Research on Transonic Wings" was mentioned as one of the important research topics in "On Topics for Advancement of Future Aircraft Technology and Plans to Achieve this Advancement" in reply to Inquiry No. 8 carried out at the Aircraft Technology Convention in December, 1971. Furthermore, "The Two-Dimensional Wind Tunnel" was given as a plan for a new facility that would be necessary in order to make this progress. The same committee noted the necessity of research on transonic wings in "Wing Sections Suitable for STOL Aircraft" during the "Basic Progress in STOL Transport Systems in Japan" session in December of 1975. Based on this information, two-dimensional wind tunnels are being planned as special wind tunnels for testing transonic wings.

2. Construction

Construction of the two-dimensional wind tunnel was planned for a 3-month period from 1973 under the instructions of Laboratory Head Yamachi and 2nd Division Head Chuken. The total budget cost was 850,000,000 yen, give or take ten thousand yen, including the cost of the additional air compressor and air tank. The first period operations were appropriated in the budget for 1973. However, this construction plan was established for cases when, from the start of construction, important tests had to be carried out. /3

At this time the industrialized countries of the world were hit with the so-called energy crisis and the increase in the cost of petroleum imports from the Middle East. The effects of this crisis were gradually felt from about May of 1973. By the end of October of the same year in which first bids for the wind tunnel were carried out, prices were in a frenzied state and these rising prices were displayed by the unsettled mood of

the market. Therefore, it was difficult to forecast the production of the wind tunnel at this time. Consequently, revisions such as omission of the first diffuser because rapid diffusion is carried out with the downflow of the pressure regulating valve, reduction of the plenum diameter from 3.3 m to 2.5 m, elimination of the settling chamber silencer and the second diffuser, etc. were carried out up to the third bid, when negotiations were broken off.

As a result of these complications it was determined that in the long run the wind tunnel could not be constructed with the initial budget. Thereupon, it was decided that the uncontracted operations would be deferred and that a new plan and budget would be made for 1973. Moreover, an additional budget would need to be made for the deficits after 1975. However, although there were difficulties in paying for the necessary budgeted items because of the trend in prices, the realization of this plan was finally forecast in the 1975 budget and therefore, the 1st and 2nd period operations were started with budgets for both 1973 and 1974. The total budgeted cost that was forecast for the construction of the wind tunnel, including the air compressor, was 1,450,000,000 yen in contrast to the original 850,000,000 yen. Completion of the project was postponed until the end of 1977.

Afterwards there were various problems with contracts and operations as construction was delayed annually for various reasons, and therefore, revisions had to be made in the budget. Moreover, during this time the supervisor in charge of the laboratory was replaced three times and the laboratory head and the division head were also replaced twice. Nevertheless, regardless of these difficulties, the supervisor and operators completed the wind tunnel itself by the end of 1977 [1] and the silencer by 1978. Production of the air compressor was finished in 1979. The entire facility was completed in 7 years.

3. Structure of the Wind Tunnel

The entire wind tunnel is shown in Figure 1. This wind tunnel is an intermittent blowoff wind tunnel. The main parameters of the design are

Test area cross section width: 0.3 m, height: 1.0 m,
Mach number range 0.2 ~ 1.2
Reynolds number 40×10^6 ($M=0.8$, $c=0.25$ m),
Wind flow duration 9 ~ 100 seconds.

The main feature of the wind tunnel is that it has a test area used for two-dimensional models and tests can be carried out with a high Reynolds number. In order to realize the aforementioned and to carry out several new tests necessary in modern wind tunnels, the following points were taken into consideration.

(a) A plug-type pressure regulating valve was employed and special care was taken so that there would be little pressure loss from this section [2].

(b) In addition to placing a porous plate and screen inside the settling chamber in order to improve air flow properties, a flat sound absorbing plate was also installed.

(c) The lower wall of the test area is a multigrooved wall and the outlet ratio can be continuously changed. Moreover, the entire test area is wrapped in the cylindrical plenum in order to make pressure resistance efficient.

(d) It is possible to control boundary layer absorption of the side walls with the model attached inside the test area.

(e) Plug-type 2nd throat valves and pressure regulating valves were used for the precharged operation system, which will be mentioned later. Moreover, the flow system at this section could be completely closed.

(f) With regard to pollution problems, special attention was given to the silencer.

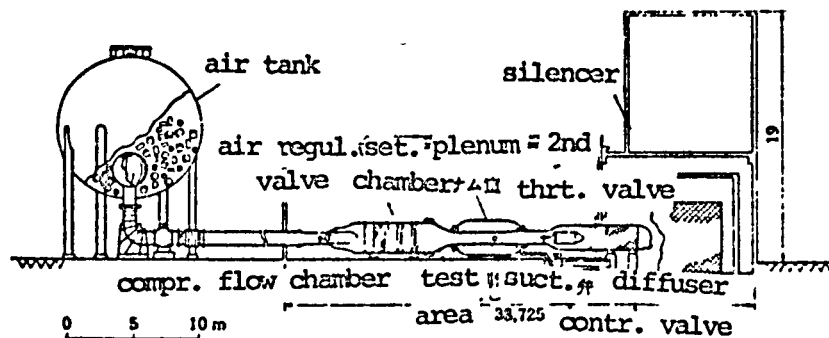


Figure 1. NAL Two-dimensional Transonic Wind Tunnel

3.1 Wind Tunnel Frame

Each component of the wind tunnel is mentioned in [3] of the bibliography. The main items will be mentioned here. With the exception of the pressure regulating valve housing, which is made of cast steel, the wind tunnel frame is made of welded steel plates. The silencer housing is made of reinforced concrete.

Pressure regulating valve: inlet tube diameter of 0.8 m; the downflow section has 9 individual diffusers lined up above it.

Settling chamber: diameter of 2.5 m and length of 6.5 m; one porous plate, 12 sound absorbing plates with a length of 1 m and width of 10 cm, and four screens (one 10-mesh screen and three 22.5-mesh screens) are installed inside.

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Compressed flow chamber [4] : sonic nozzle, length of 2.5 m, compressed flow ratio of 16.35:1.

Test Area: width of 0.3 m, height of 1 m and length of 3 m (section where the groove width of the multigrooved wall is constant), top and bottom multigrooved wall opening ratio of 0-10%, the downflow opening angle can be varied by $\pm 0.7^\circ$.

A glass window or sintered metal plate (boundary layer absorption plate) with an effective diameter of 0.465 m and a thickness of 0.01 m can be attached to the side walls to which the model is attached when necessary for the experiments.

Range at which the angle of incidence of the model can be varied -- $15^\circ \sim 25^\circ$.

Grooves used for the flow measurement probe are located behind the downflow 0.7 m from the center of the model attachment. The probe can travel up and down these grooves 800 mm.

Television cameras are installed above and below the model attachments to observe the model and the air flow.

Plenum: diameter of 2.8 m, glass observing window with a diameter of 0.25 m and a thickness of 95 mm

After suction control valves are placed at right angles to the air flow from the right and left of the plenum, they are joined together as one valve and the plenum is then connected to the inside of the silencer with this suction control valve (250 mm rotary valve).

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2nd throat valve: inlet tube diameter of 0.8 m Diffuser (5): contains 2 porous plates (the opening ratio is 27% at the upward flow side and 49.7% at the downflow side); the downflow bottom has the same porous cylindrical surface as the downflow side porous plate.

Silencer (Figure 2): has a width of 10 m, height of 19 m, and a length of 40 m on the outside; part of the silencer was constructed in two stages with double walls. The silencer is a flat plate-type silencer. There are seven large sound absorbing plates, 13 medium-sized sound absorbing plates, and 21 small sound absorbing plates inside the silencer. The size of each sound absorbing plate is, respectively, 0.9 m x 7.35 m x 5 m, 0.7 m x 7.9 m x 2.5 m, and 0.4m x 7.9 m x 2.5 m (width x height x length).

The actual reduced sound property is 82 db (O. A.).

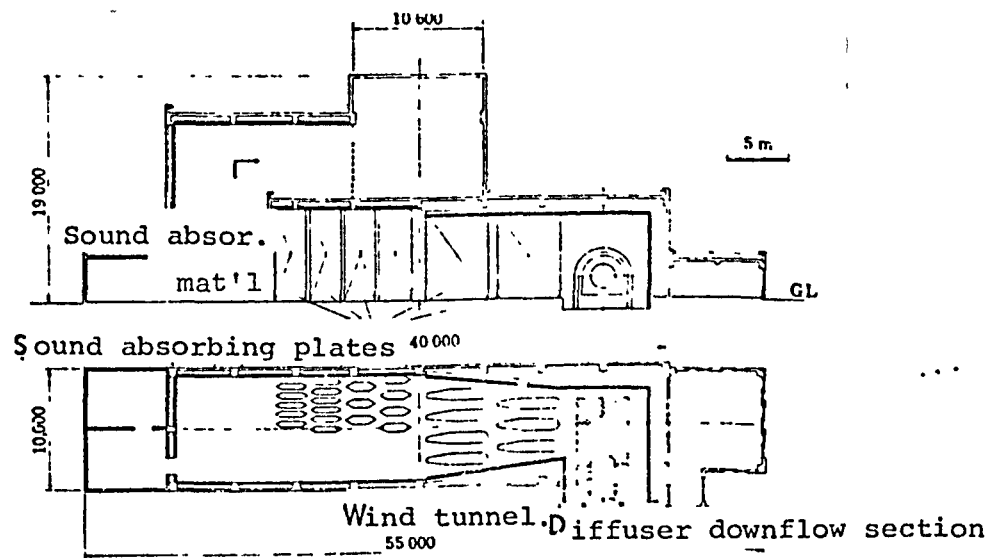


Figure 2. Silencer used in the Two-Dimensional
Wind Tunnel

3.2 High Pressure Air Source

The high pressure dry air (maximum pressure of 21 kg/cm^2 abs., / 5 dew point temperature of -59°C) comes from the air compressor and high pressure air tank shown below, which can be used with other wind tunnels:

return-flow air compressor: $900 \text{ kW} \times 1$, discharges $6,000 \text{ Nm}^3/\text{h}$;
Lysholm air compressor: $1200 \text{ kW} \times 1$, discharges $6,000 \text{ Nm}^3/\text{h}$;
centrifugal air compressor*: $3450 \text{ kW} \times 1$, discharges $18,000 \text{ Nm}^3/\text{h}$;
1st and 2nd air tanks: diameter of 10 m and capacity of 523.3 m^3 each;
3rd air tank*: diameter of 12 m and capacity of 904.3 m^3 .

3.3 Measuring Devices and Data Processing Equipment

In the wing section tests with this wind tunnel the lifting power evaluations were carried out by measuring the pressure distribution over the wing model. Drag evaluations were carried out with backflow (wake) measurements. A balance system to measure the three force components was not set up. Four scanning valves were used to measure the pressure distribution over the model. After this analog data was amplified, it was recorded on a data processing disk through an analog digital converter. After the experiments, the important data were transferred to magnetic tape and sent to the computer center where computations were carried out, or the tape was transmitted to the CPU of the computer center, where the necessary computations were carried out. Moreover, after the experiments, simple computations

*These devices were set up according to the wind tunnel facility preparation plans. The air compressor should be completed by the end of 1979.

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can be carried out with a minicomputer used in recording the wind tunnel data, which would also serve as a monitor (YHP MX-1000 series 2171). Then these results would be output from the line reader, the graphic display device, etc. (should be completed in 1979). Figure 3 is a block diagram of the data processing equipment.

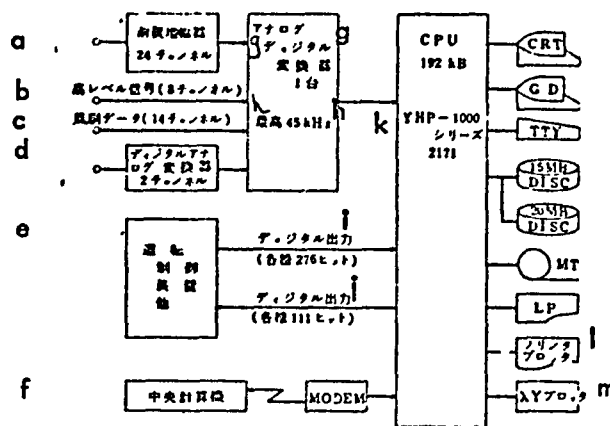


Figure 3 Block Diagram of
the Measuring Devices and
Data Processing Equipment

- Key: a. forward amplifier, 24 channel; b. high level signal (8 channel);
c. wind tunnel data (24 channel); d. digital analog converter, 2-channel;
e. operation control room location;
f. central processing unit; g. one analog to digital converter;
h. maximum 45 kHz; i. digital output (each type 276 bits);
j. digital output (each type 111 bits); k. YHP-1000 series 2171;
l. printer-plotter; m. XY plotter

3.4 Operation Control Devices

There are devices to control each of the valves and movable parts of the wind tunnel components in accordance with the necessary program. Each component is hydraulically driven (pressure of 140 kg/cm^2). Each part can be automatically driven during air flow in accordance with the program that is being used by setting the times for valve opening and closing, etc. prior to air flow. The operation control features of this wind tunnel are as follow.

(a) It is possible to control the Mach number. That is, the Mach number is measured during air flow and automatically controlled so that it is a set value by feeding the Mach number directly into the control device. Therefore, this differs from conventional wind tunnels only in that the Mach number can be set.

(b) After the pressure is detected and converted to digital signals to carry out the necessary computations in the control systems for the pressure regulating valve, the 2nd throat valve, and the suction control valve, the computations are converted to analog signals and transmitted to the actuator. Thus, a semidigital control system is employed to improve the control precision for the settling chamber pressure, Mach number, etc. The angle of incidence of the model is controlled with an analog system, and plans, detection, etc. are controlled with a digital system. The angle of incidence can be continuously changed within a set angle range or changed in steps whereby a pitch-pause mode is repeated with 10 different angles of incidence being obtained. /6

(c) In addition to conventional operation systems for blowoff type wind tunnels, precharged operations systems may also be employed. This is the method whereby after air near the preset settling chamber pressure is stored between the pressure regulating valve and the 2nd throat valve prior to air flow, the state of air flow is entered by opening the 2nd throat valve and the pressure regulating valve. This precharged operation system is used to carry out high Reynolds number tests (tests with a high settling chamber pressure). The advantages of this system are

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mentioned below.

(i) In addition to the air stored in the 1st-3rd air tanks, the settling chamber of this wind tunnel also stores air and therefore, there is an increase in the amount of air stored in the tunnel and consequently, air flow lasts longer.

(ii) With conventional operations systems it is necessary to compress the air in the wind tunnel by penetrating the high pressure air from the pressure regulating valve and therefore, the temperature increases. This type of drastic change is avoided with precharged operation system. By avoiding these drastic changes, poor air flow conditions and destruction of the model can be avoided.

(iii) Because the air tunnel is operated at a condition near a set settling chamber pressure, it is possible to reach normal conditions in a short amount of time.

The aforementioned wind tunnel components are shown in Figures 4-8. Moreover, one example of a schlieren photograph is given in Figure 9.

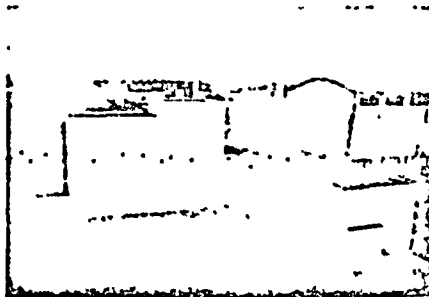


Figure 4. Two-Dimensional
Wind Tunnel, Outside appearance;
front view: silencer;
bottom right: wind tunnel building.

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Figure 5. Two-Dimensional Wind Tunnel
Pressure regulating valve.
Bottom right: bypass valve for precharged air operation.

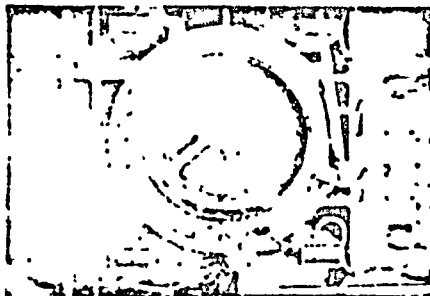


Figure 6. Test section
(Model having an angle of incidence).

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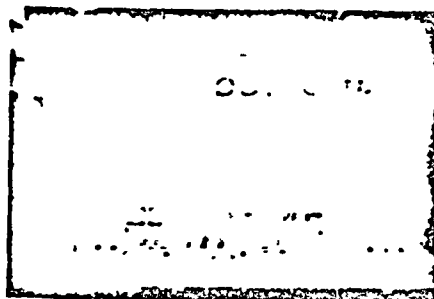


Figure 7. Operation Control
Board.

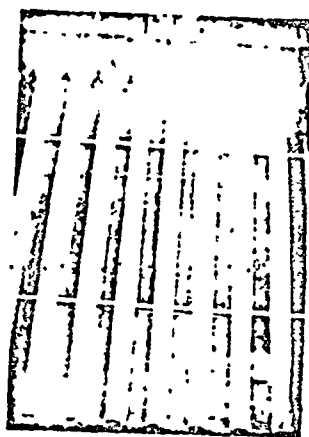


Figure 8. Inside of Silencer
(Acoustic panels).

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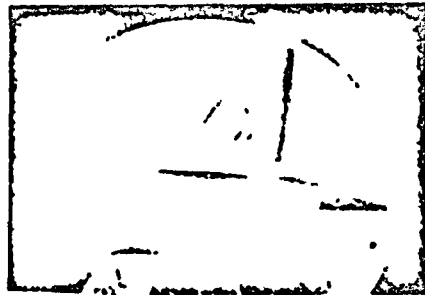


Figure 9. Schlieren Photograph
(wing section NACA 64A410, $M=0.849$, $\alpha=2^\circ$, $R_e=1.4 \times 10^7$).

4. Operation Test Results

Some of the data processing equipment and air compressors have not been completed yet. However, as most of the wind tunnel facility was complete, it was determined that air flow tests could be carried out and therefore, 141 tests were performed over a period of four weeks since June 25 of this year.

4.1 Overall Performance

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The experimental capability range of this wind tunnel is shown in Figure 10. Air could be passed safely at the O marks in the Figure. Normal conditions were obtained after a certain amount of time and it was shown that various types of wind tunnel tests are possible. The maximum Mach number is somewhat lower than planned values, at 1.15. The duration of normal conditions, which was computed from the experimental results, is also shown in the Figure, which will be explained later. Normal conditions were maintained for the shortest amount of time when tests were carried out with a high Mach number and maximum Reynolds number. However, even under these conditions, normal flight could be maintained for 5 seconds. This was the exact amount of time

necessary to test one angle of incidence.

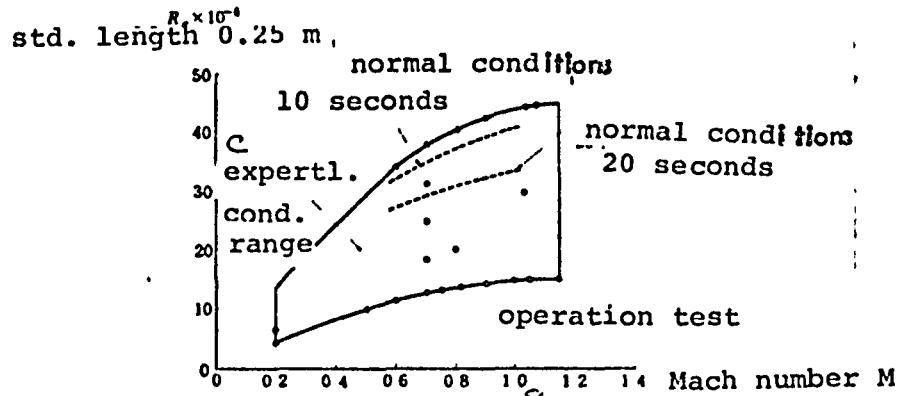
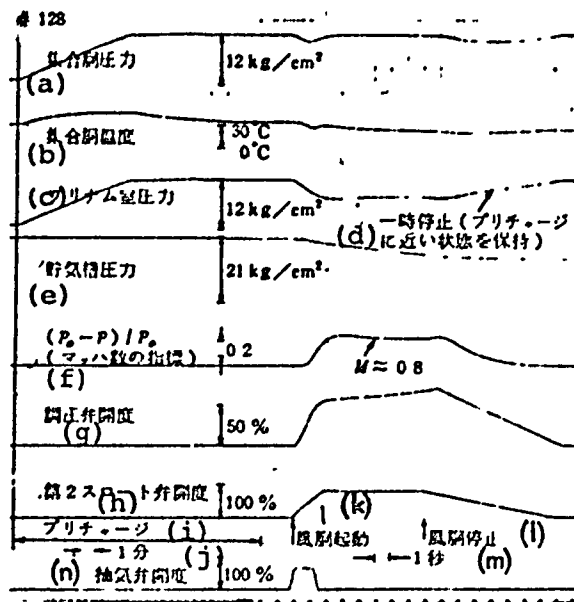


Figure 10. Experimental Capability Range:
Reynolds number versus Mach number.

Changes in the operating conditions, pressure, pressure ratio (function of the Mach number), etc. of the essential devices in the wind tunnel during air flow are shown in Figure 11.

These recordings were taken with a settling chamber pressure of 12 kg/cm^2 abs., a set Mach number of 0.8, and an air flow time of 8 seconds. Five seconds after air flow, the Mach number $((p_0 - p)/p_0)$ became constant and normal conditions were maintained for about 3 seconds.

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- Key: a. settling chamber pressure, p_0 ; b. settling chamber temperature;
c. plenum pressure, p ; d. temporary shut-off
(state near precharged
condition maintained);
e. air tank pressure; f. pressure ratio $(p_0 - p)/p_0$ indicator
of Mach number;
g. pressure regulating valve opening; h. 2nd throat valve opening; i. precharged;
j. 1 minute; k. wind tunnel operation; l. wind tunnel shut-off;
m. 1 second;
n. suction control valve.

Figure 11. Oscillograph trace of the precharged air operation and wind tunnel blow.

4.2 Duration

Just as air is blown off from a tank with a finite capacity in a blowoff type wind tunnel, the during which which air can flow is also finite. Air can usually flow for a period of from ten-odd seconds to several tens of seconds. Because an air current was obtained at a high Reynolds number with this wind tunnel, the gaseous density is high when the pressure is high. Consequently, in comparison to wind tunnels having the same air path cross section area, the same Mach number, and a low Reynolds number, the amount of air flow is as large as the density is large and therefore, there is a disadvantage with regard to duration. Furthermore, there is even more of a disadvantage with regard to the excess blowing pressure, which will be explained below.

Duration is found by dividing the amount of air available in the air tank by the amount of air flow during the Wind tunnel tests. In the evaluations of the amount of air that is available it is necessary to determine

(a) the amount of air in the air tank from the beginning of air flow until normal conditions are obtained, or that is, the amount of air pressure lost by the air tank;

(b) and the surplus of air pressure inside the air tank after normal conditions are finished.

These were computed from experiment results with a settling chamber pressure of 12 kg/cm^2 abs. With regard to (a), the ratio of the air tank pressure when normal conditions were obtained during air flow and the air tank pressure when air flow began was 0.85, which was somewhat lower than the predicted value (0.9), when the 1st-3rd air tanks were employed (can be adjusted by the control system). However, the ratio of the settling chamber pressure to the air tank pressure when normal conditions were finished in (b), 1.2, was much better than the predicted value (1.4). Therefore, good results were obtained with the pressure regulating valve.

The duration of normal conditions can be computed with this value with any experimental conditions. Some of these results have been recorded in Figure 10.

4.3 Precharged Operation

As was mentioned in section 3.4, both conventional operations for blowoff type wind tunnels and precharged operations are possible with this wind tunnel. The majority of the tests carried out here were performed with the precharged operation method and there were no particular problems. This precharged operation method is characterized by the fact that it is carried out with a high, fixed settling chamber pressure. Conventional operation methods cannot be carried out when the fixed settling chamber pressure is high. Therefore, a comparison of the two systems with a relatively low settling chamber pressure is shown in Figure 12. The amount of time until standard conditions are obtained is the same with both systems. Moreover, with both systems the Mach number reaches standard conditions in 1-1.5 seconds after the settling chamber pressure p_o has reached standard conditions. It seems that because the gain, integral time, etc. of the control systems of both methods cannot be adjusted to the optimum values, the transient times shown in Figure 12 18 can be curtailed even further to 1-2 seconds.

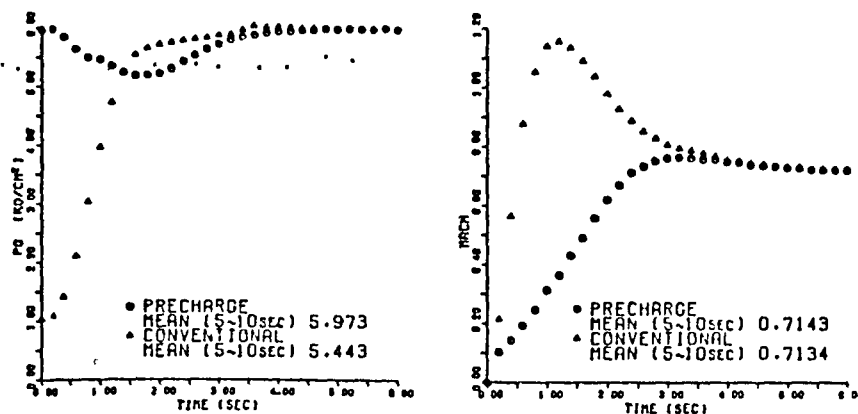


Figure 12. Comparison of Precharged Operation System and Conventional Operation System-I:

Left -- settling chamber pressure;
Right-- Mach number.

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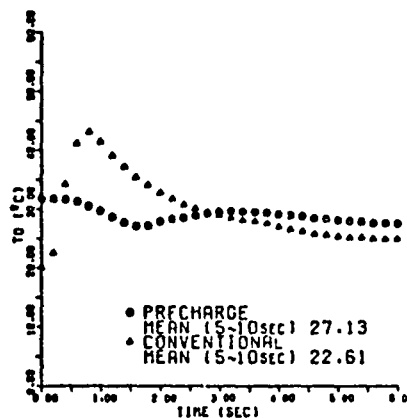


Figure 13. Comparison of Precharged
Operation System and Conventional
Operation System-II:
Settling chamber temperature.

4.4 Other Items

The following items should be mentioned with regard to the operation tests results.

(a) The time necessary for reaching standard conditions can be decreased to 0.5-1 second by employing the Mach number control (3.4(a)).

(b) It is common for the test area wall pressure distribution to be uniform. However, when the air flow near the section where grooves are employed for the measuring probe behind the downflow of the model attachment accelerates, the uniformity of the Mach number in this region is destroyed.

(c) The silencer was effective. Sounds from the wind tunnel were eliminated at the entrance on the south side, the computer room on the west side, the large, low speed wind tunnel on the southwest side, etc. Noise from the wind tunnel was heard between the Power Division on the north side and the laboratory. However, this noise was probably produced from the high pressure duct between the air tank and wind tunnel.

5. Future Plans

Tests on the Mach number distribution and standardized model pressure distribution (NACA 64A410) will be carried out in the last half of 1979. Wing section systems tests will begin in 1980.

In conclusion we would like to express our thanks to the 2nd Aerodynamic Research Laboratory and in particular to Supervisor Chuken, and to Kawasaki Heavy Industries, Ltd., Ishikawajima Hoon Kogyo Co., Ltd., Yokogawa Hewlett Packard Co., Ltd., Marunichi Watanabe Construction Co., Ltd., Hajima Construction Co., Ltd., and Angawa Electrical Equipment Co., Ltd.

(2nd Aerodynamic Research Laboratory)

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